RAINSTORM IN SOUTHERN FLORIDA, JANUARY 21, 1957

ROBERT H. SOURBEER AND R. CECIL GENTRY

National Hurricane Research Project, U.S. Weather Bureau, Miami, Fla.

[Manuscript received November 5, 1959; revised September 29, 1960]

ABSTRACT

The storm situation of January 21, 1957, is studied and the vorticity and horizontal divergence patterns are computed from analyzed synoptic maps at low and high elevations of the troposphere. Contour and streamline charts for the period are presented to show that consideration of many of the synoptic parameters ordinarily used in analysis and forecasting would not lead one to expect such heavy rainfall. Computations of divergence are compared with the rainfall charts in an effort to determine the cause of the heavy rainfall which varied in amount up to 21½ inches within a 24-hour period. The divergence patterns move horizontally with time in such a manner that a high-level divergence area becomes superimposed over a low-level convergence area at the time of heavy rain.

1. THE RAIN

Over 21 inches of rain fell in a limited area in southern Florida during a rainstorm on January 21, 1957. Figure 1 shows the rainfall distribution, in inches, for the storm. Amounts of 21.03 and 21.04 in. were recorded at West Palm Beach Water Co., gages 1–40 and 2–25, respectively, both of which are about 5 miles southwest of the West Palm Beach Airport. A few miles farther south a fall of 21.5 inches was recorded at the farm of Dan Smith. His gage is a small plastic one which reads to only 5 inches. However, Mr. Smith, watching the rain from a packing shed, dumped the gage each time it reached 4½ inches; this occurred 4 times with 3.1 additional for a total of 21.1. However, there was a spray barrel on the grounds which had been rinsed and drained the day before. After the rain (next day) Mr. Smith measured 21.5 inches of water in the barrel.[1] He stated that 16 inches fell between 11 a.m. and 4 p.m. EST.

Over 9 inches of rain fell at recording stations along the southeastern shore of Lake Okeechobee. Of these amounts an average of 6 to 7 inches fell between 4 a.m. and 10 a.m. EST, and less than 0.20 after 4 p.m. Five miles inland from Boca Raton, 17 to 18 inches of rain were recorded during the duration of the storm. Along the Atlantic Coast and at the Weather Bureau Airport Station at West Palm Beach the total was 6.33 inches, of which 4.70 inches fell between 5 p.m. and 7 p.m. EST, and only 0.04 after midnight.

The rainstorm as a whole moved from west to east. A time series of pictures taken of the radarscope at the University of Miami [1] shows that while the main rain cell was moving slowly eastward it was continually being reinforced by small cells that moved in from the east. (One picture is shown in fig. 2).[2] Rain cells dissipated as they departed to the west from the main rain core. This suggests that perturbations which triggered the beginning of showers were moving from east to west.

2. DATA FOR FORECASTING

Many of the parameters ordinarily considered in rain forecasting would indicate that little or no rain should have been expected on that particular day; e.g., the streamlines and contours at almost all tropospheric levels were either straight or had anticyclonic curvature. Only at 850 mb. and 500 mb. was there even weak cyclonic curvature, and

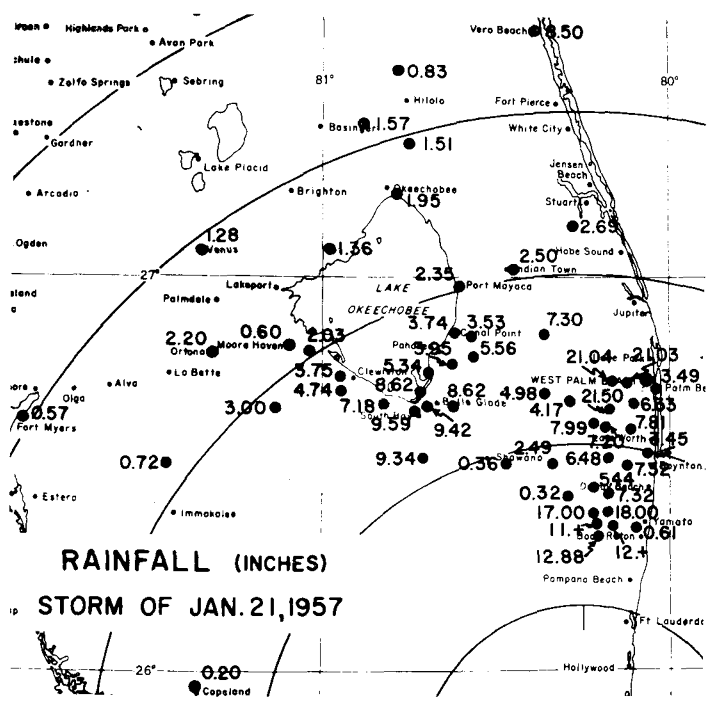


FIGURE 1.—Rainfall (inches) for the storm. Most of the rain fell in less than 24 hours. The very heavy rainfall lasted less than 5 hours at most stations.

[1] Reported by Jack L. Hudnall, Meteorologist in Charge, Weather Bureau Airport Station, West Palm Beach, after interviewing Mr. Smith.

[2] Prepared and analyzed by Mr. L. F. Conover from pictures taken at the Radar Laboratory, University of Miami.

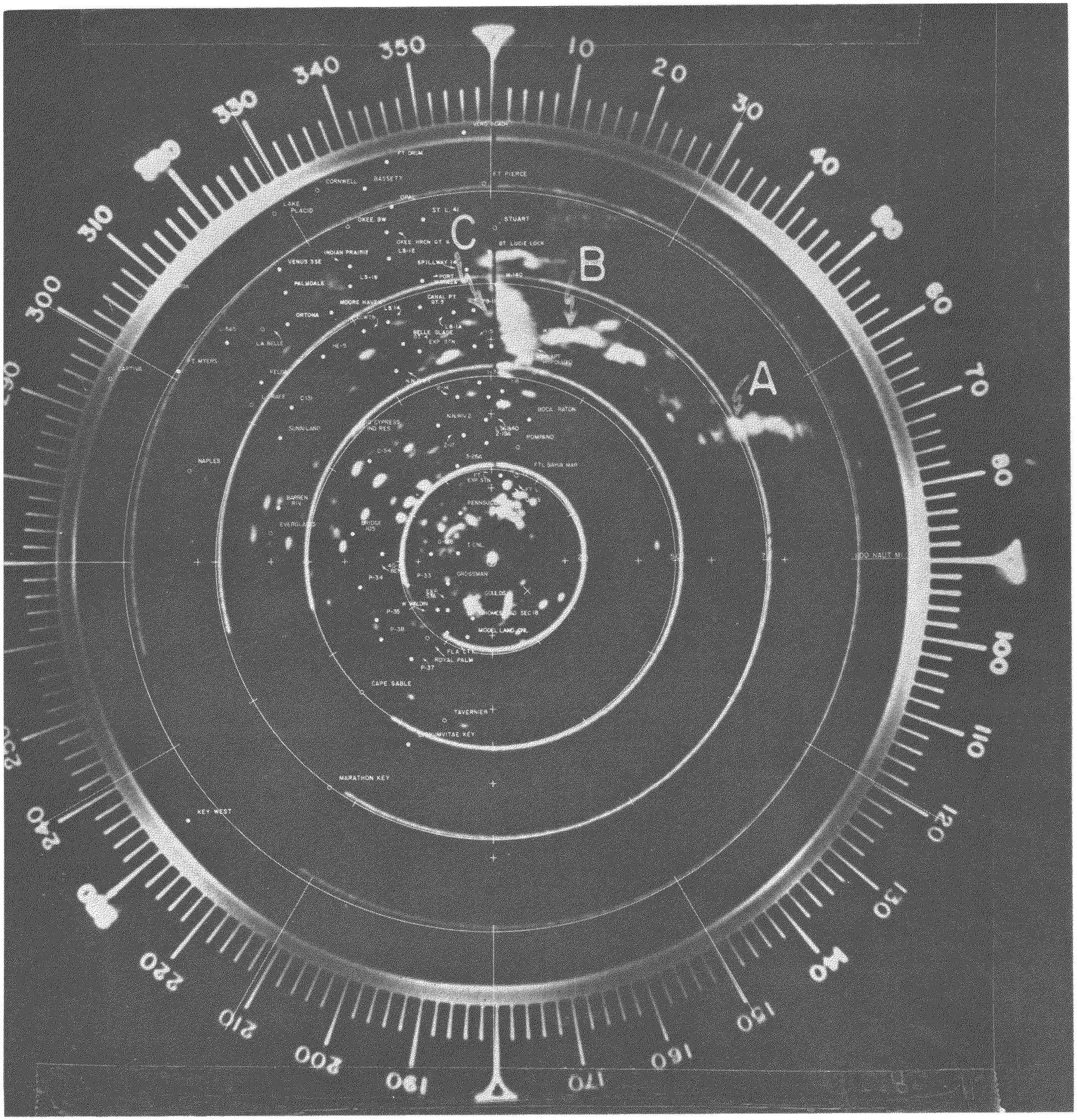


FIGURE 2.—Pictures of radar scope taken at University of Miami, January 21, 1957. Echo "C" was quasi-stationary. Echoes "A" and "B" were moving toward the west-northwest at about 30 m.p.h. Note that the echoes moving westward out of the main rainstorm (echo "C") were relatively weak and dissipating. Echo "C" was over area where over 21 inches of rain fell.

at 700 mb. a weak ridge covered the area of intensive rainfall. Much of the cloudiness could be topped at 10,000 to 12,000 feet.

According to pilot reports there were isolated clouds that extended to great elevations. The soundings taken at Miami and Cocoa indicated the lapse rate was convectively unstable.

In this paper streamline maps at 2,000 feet and 250 mb., and maps of the divergence patterns at each of these levels, are reproduced. The heavy rainfall will be attributed to the divergence associated with the high-level jet over the area on January 21.

At the time of the heavy rain an area of divergence at the 250-mb. level, moving from the west-northwest,

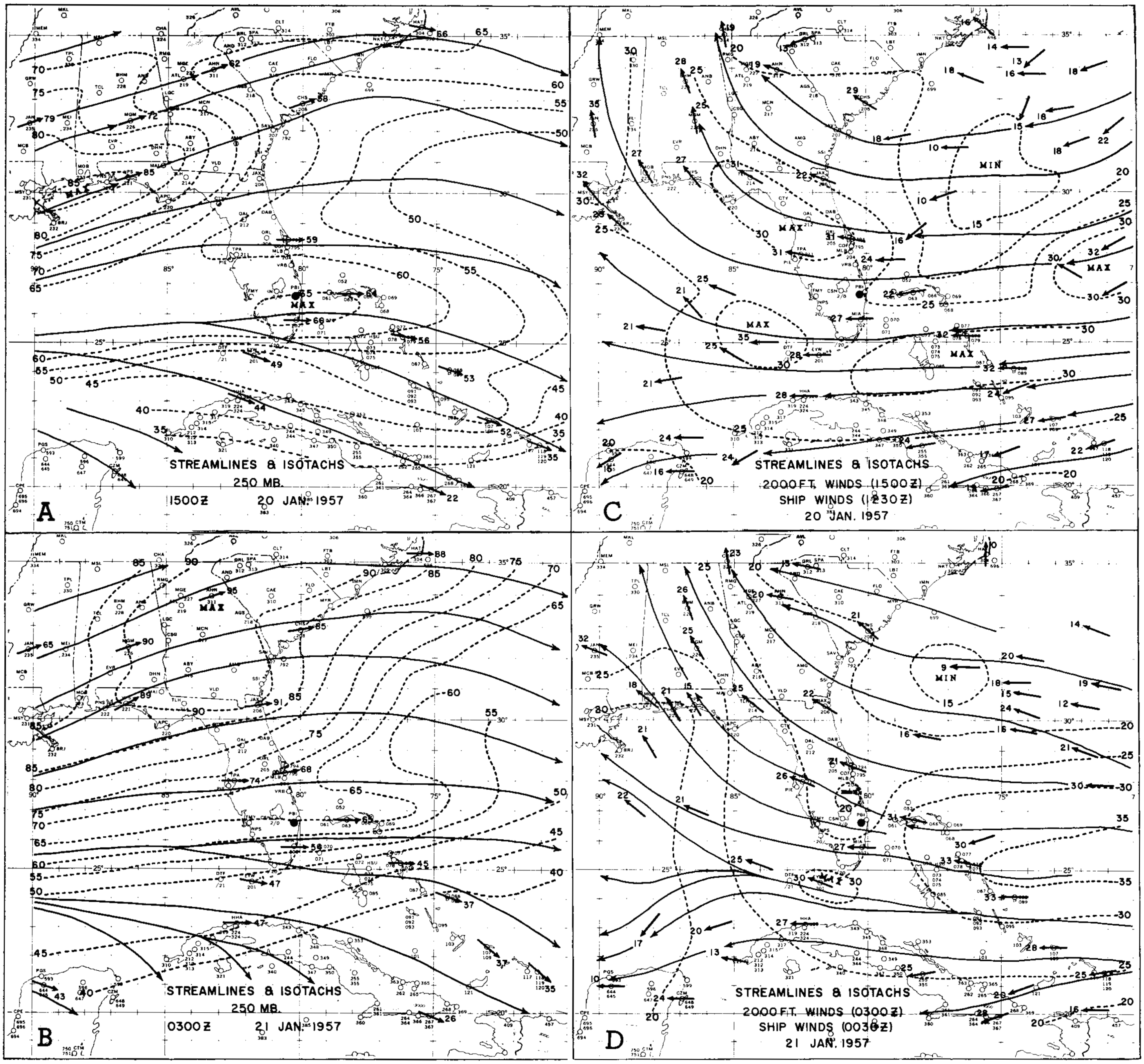


FIGURE 3.—Streamlines (solid) and isotachs in knots (broken) for the day preceding the heavy rain. (A) 250 mb., 1500 GMT, Jan. 20; (B) 250 mb., 0300 GMT, Jan. 21; (C) 2,000 ft., 1500 GMT, Jan. 20 (Ship winds at 1230 GMT); (D) 2,000 ft., 0300 GMT, Jan. 21, 1957 (Ship winds at 0030 GMT). The black dot near West Palm Beach marks the location of the heaviest rainfall.

arrived over the area coincident with the arrival of an area of convergence in the low-level wind field which moved in from the east-southeast. The time-lapse movies of the radarscope located at the University of Miami reveal a movement pattern of the echoes which lends support to these hypotheses.

Streamlines and isotach charts are presented in figures 3 and 4. (The heavy rain started a little before the time of the first two charts in figure 4 and was over by the time of the second two.) At both levels the streamlines are either straight or curved anticyclonically. The clue to the cause of the rain seems to be in the speed field. If the speed and moisture fields were omitted from these charts, there would be little to suggest that heavy rainfall would occur over southern Florida.

There are several features which are worthy of note. The decrease in speed in the low-level winds as they blew toward shore was undoubtedly a contributory cause of

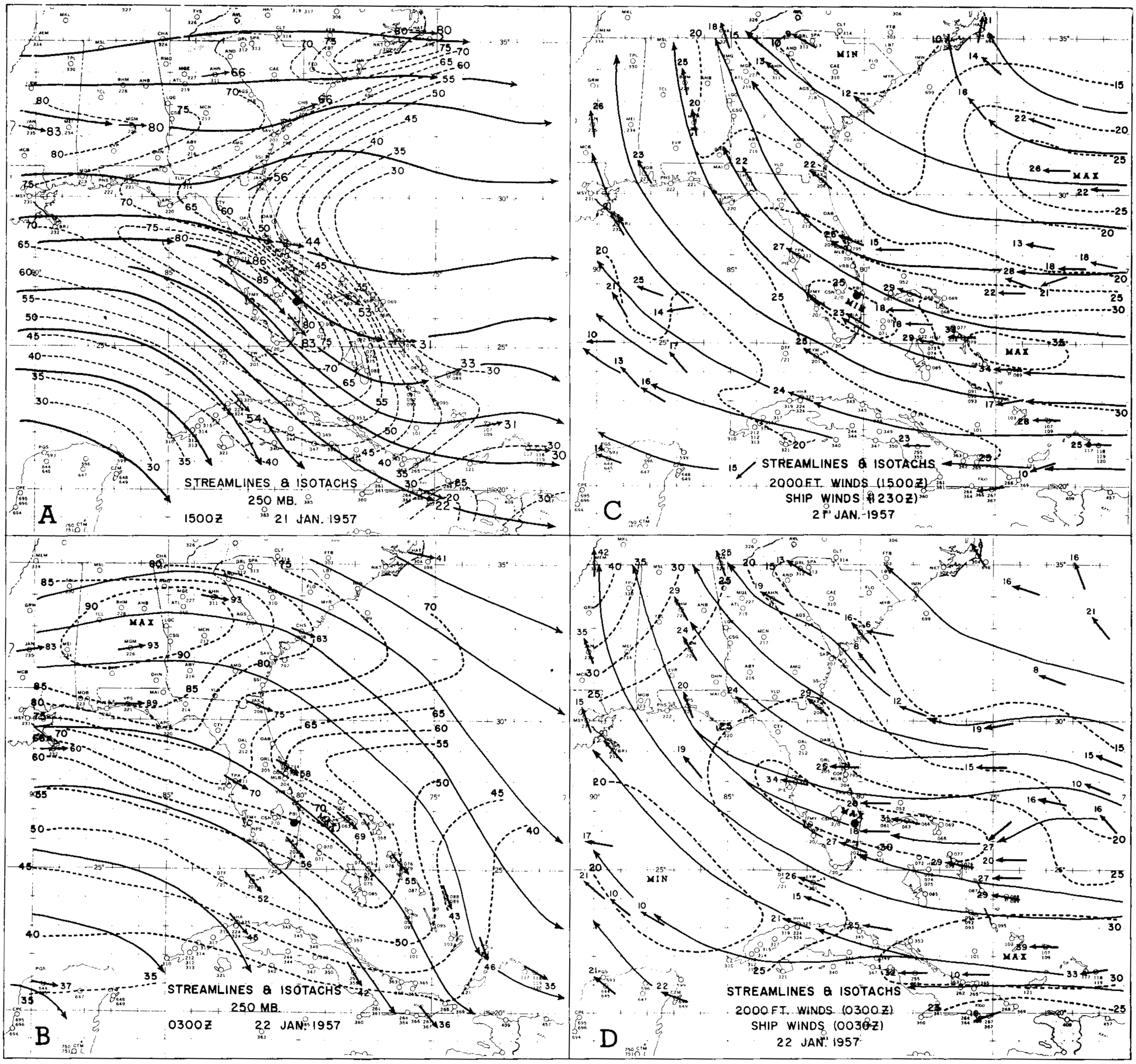
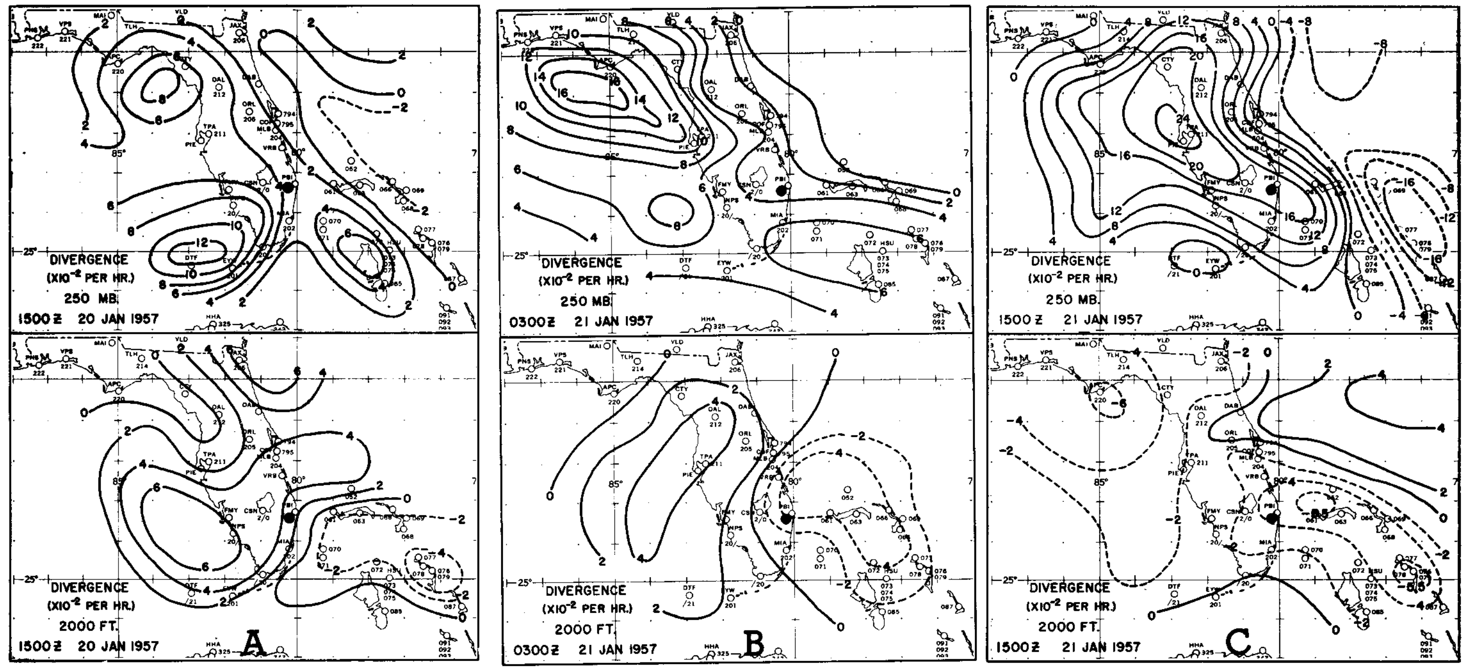


FIGURE 4.—Streamlines and isotachs (kt.) for the day of heavy rainfall. (A) 250 mb., 1500 GMT, Jan 21; (B) 250 mb., 0300 GMT, Jan. 22; (C) 2,000 ft., 1500 GMT, Jan 21 (Ship winds at 1230 GMT); (D) 2,000 ft., 0300 GMT, Jan. 22 (Ship winds at 0030 GMT). Black dot shows location of heaviest rain.

the rain. Note also the change at 250 mb. between 0300 GMT and 1500 GMT on the 21st (figs. 3B and 4A). The streamlines became more northwesterly and the jet stream very pronounced by 1500 GMT, at about the time the heavy rains began. Apparently the jet moved eastward across the state and weakened by 0300 GMT on the 22d, (fig. 4B) which is about 3 hours after the end of the heavy rain. The dot (figs. 3, 4, and 5) locates the area in which the rainfall was in excess of 21 inches. This was on the low pressure side of the jet stream and in advance of the maximum wind speed (fig. 4A). This is one of the areas (relative to the jet maximum) and the preferred one where, from vorticity considerations, one would expect to find divergence at the upper levels [2,3,4]. The argument of this paper is that the heavy rainfall was caused by the coincidence of divergence at high levels over the area of



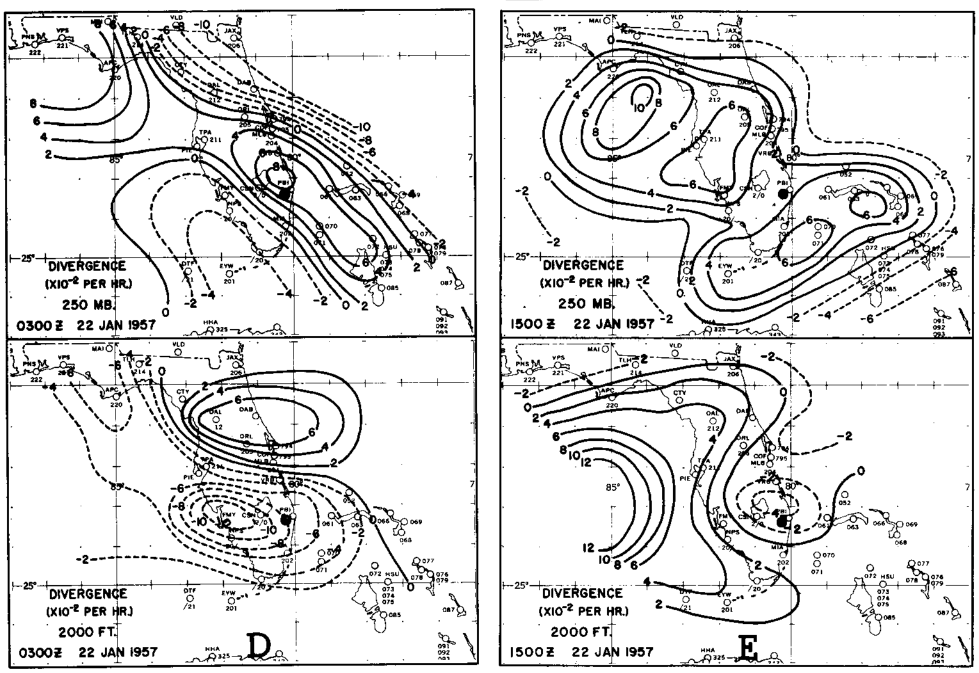


FIGURE 5.—Divergence (solid lines) and convergence (dashed lines) in units of 10^{-2} hr.$^{-1}$ for the 250-mb. level (upper chart of each pair) and the 2,000-ft. level (lower chart). (A) 1500 GMT, Jan. 20; (B) 0300 GMT, Jan. 21; (C) 1500 GMT, Jan. 21; (D) 0300 GMT, Jan. 22; (E) 1500 GMT, Jan. 22, 1957. Black dot shows location of heaviest rain.

convergence at the lower levels. It is the wind speed field which seems to bear the greatest causal relation to what happened in the weather.

3. HORIZONTAL DIVERGENCE COMPUTATIONS

The results of the computations of horizontal divergence made from the analyses are presented in figure 5. The divergence and vorticity were each computed with a Graham computer [5] for an equilateral triangular area of approximately 120 nautical miles altitude centered on each point in the grid shown in figure 6. (Vorticity charts are not reproduced.) Since the subjective analyses of the isogon and isotach charts influenced the computations, each of the wind charts was analysed by three analysts working independently. Although there were differences in values of divergence and vorticity at given points computed from the three independent isogon and isotach analyses, locations of areas of maximum and minimum divergence were approximately the same for any given time.

Consideration of the vertical moisture gradient existing over southern Florida at the time makes it clear that it was necessary to have convergence in the first few thousand feet above the surface and ascending motion high into the troposphere for sufficient moisture to be removed from the air to account for the heavy rains observed. Thus for the period and area of heavy rainfall there should have been appreciable convergence in the lower layers (e.g., 2,000 feet), and in the upper layers (e.g., 250 mb.), and only one important layer of non-divergence in between. At the 250-mb. level, from 1500 GMT, January 20, to 0300 GMT, January 21 (fig. 5A–C), the strong area of divergence was building up in the eastern and northeastern Gulf of Mexico for about 24 hours before the heavy rains began. At 1500 GMT January 21, the area of divergence reached its maximum intensity and moved across southern Florida. By 0300 GMT on the 22d, (fig 5D) by which time the rain had about stopped, the divergence had decreased in intensity and moved off the southeastern coast of Florida.

At the lower level the area of convergence which was located off the southern Florida coast at 1500 GMT, January 20, (fig. 5A) expanded and moved westward until the leading edge was over Lake Okeechobee by 0300 GMT, January 21. At 1500 GMT, January 21, (fig. 5C) the area of convergence had become better organized with a more intense center just east of West Palm Beach. At 2100 GMT on the 21st (chart not shown), the center was about 30 miles northwest of Miami with greater values than those shown for 0300 GMT on the 22d (fig. 5D). From this series of charts, indications are that the convergence at low levels intensified rapidly shortly after 1500 GMT and moved westward across southern Florida, and then dissipated, except for a small area along the coast just north of West Palm Beach, between 0300 and 1500 GMT January 22.

Computations of divergence, necessary to account for the observed rainfall, can be used as an order of magnitude check on divergences computed from the analyzed wind fields. To a reasonably close approximation

$$-\overline{D}_i \approx \frac{gR}{\Delta p_i(\overline{q}_i - q_u)},$$

where $\overline{D}_i$ is the mean divergence in the inflow layer, g is acceleration of gravity, R is rainfall rate, Δp_i is difference in pressure between top and bottom of the inflow layer, $\overline{q}_i$ is mean specific humidity of air in the inflow layer, and q_u is specific humidity of moisture flowing out of the rain area. From 1500 GMT January 21 until 0300 GMT January 22, average areal rainfall for a triangle of the size indicated in figure 6 in the area of greatest rainfall was about 0.1 cm./hr. If $\Delta p_i = 150$ mb., $\overline{q}_i = 11$ gm. kg.$^{-1}$ (indicated by the soundings), and $q_u = 3$ gm. kg.$^{-1}$ (assumed) the convergence in the inflow layer is approximately 8×10^{-2} hr.$^{-1}$. This is the same order of magnitude as the maximum values of convergence on the charts in figure 5. At the Dan Smith farm, rain fell at the rate of about 9 cm. hr.$^{-1}$ between 11 a.m. and 4 p.m. If the same assumptions for Δp_i, q_i, and q_u are used, the mean

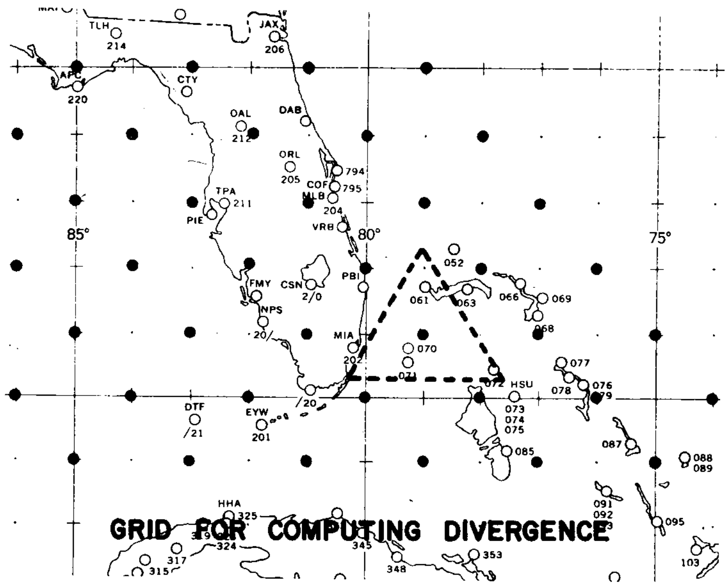


FIGURE 6.—Grid for which divergence computations were made. Computations were made for areas the size of the triangle, centered at each heavy dot.

convergence in the inflow layer is approximately $+7.4$ hr.$^{-1}$. This is obviously much greater than any convergence indicated by the wind reports, and mass compensa-

TABLE 1.—*Horizontal divergence* (10^{-2} *hr.* $^{-1}$), *January 20–22, 1957*

Height 10^3 ft.	January 20	January 21		January 22	
	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT
A. Miami, Cocoa, Grand Bahama Triangle					
50	5.40	15.05	−5.94	8.82	1.44
40	−2.70	5.83	25.70	−1.04	−34.20
(250 mb.)	0.11	13.75	32.72	19.76	10.19
30	−0.54	5.83	24.12	8.68	1.40
25	9.11	−3.49	18.61	−2.66	3.13
23	3.56	4.14	21.38	0.22	-----
20	8.96	5.54	1.12	14.54	0.61
18	16.20	8.93	−2.99	5.04	−3.24
16	7.20	4.10	−6.84	15.05	−1.55
14	−0.54	8.81	−7.20	11.95	−7.20
12	1.12	-----	−11.45	9.40	2.59
10	1.69	-----	−12.85	−0.54	4.46
8	−4.39	-----	−4.64	−2.99	−4.18
6	3.82	-----	−6.44	4.03	1.76
5	4.39	-----	−8.32	−0.40	−1.73
4	1.66	-----	−2.48	−8.42	0.32
3	1.04	-----	−5.11	−3.02	-----
2	8.86	-----	−7.67	−10.69	4.61
1	8.71	9.68	−7.63	−10.04	−1.80
B. Miami, Cocoa, Tampa Triangle					
50	−13.39	-----	-----	−4.72	−8.17
40	-----	5.29	7.99	1.08	−19.66
(250 mb.)	4.39	−0.50	3.02	−3.31	19.84
30	−3.17	10.87	24.41	−12.35	−4.72
25	−6.48	1.98	30.78	−1.40	0.50
23	−10.48	3.20	23.18	11.63	−4.00
20	0.54	0.72	20.23	20.59	0.07
18	4.21	10.66	23.62	12.92	−3.38
16	−0.58	0.32	4.18	11.27	5.81
14	2.05	4.28	11.20	−6.84	11.02
12	1.01	-----	−5.15	−3.49	11.74
10	−2.66	-----	−1.22	−21.49	16.42
8	−11.38	-----	7.92	−17.89	−0.04
6	−3.82	-----	1.73	−9.43	1.08
5	4.00	-----	−1.01	−3.85	−6.66
4	5.80	-----	−6.55	−5.26	−8.71
3	1.08	-----	−6.52	0.58	−2.41
2	3.96	-----	−1.58	1.69	0.76
1	0.40	3.89	−5.44	−2.38	−4.32

tion in the vicinity of the torrential rain must have taken place within a much smaller area than that of the triangles considered in this study.

To check the validity of the divergence computations which were made from subjective analyses, the winds at Cocoa, Grand Bahama, Miami, and Tampa were used to compute in an objective manner the divergence for two triangular areas [6]. In table 1 the results of these computations are presented for the same times as the 250-mb. and 2,000-ft. charts. Table 1A gives the divergence computations for the Miami, Cocoa, and Grand Bahama triangle. Table 1B is for the Miami, Cocoa, Tampa triangle. Note at 1500 GMT on the 21st, near the time of the beginning of the heavy rain, the extremely large values of divergence at upper levels and the convergence at low levels. In general the objective computations of divergence support the more detailed computations based on the subjective analyses.

The vertical motion (averaged over the area) can be computed from the divergence values given in table 1 by using the trapezoidal rule [6],

$$w_n = w_{n-1}\frac{\rho_{n-1}}{\rho_n} + \left[D_{n-1}\frac{\rho_{n-1}}{\rho_n} + D_n\right]\frac{\Delta z}{2},$$

where w is vertical velocity, ρ is density, D is divergence, subscripts n and $n-1$ refer to levels, and Δz is thickness of layer. These computations can be made either by letting $w_0=0$ or by assuming w at the height of the tropopause (about 40,000 feet) to be the same as the mean change in height of the tropopause for a 24-hour period centered on time of observation. Maximum vertical velocities given by these computations are given in table 2. In three of the four cases the maximum tropospheric vertical velocities computed from the two different boundaries are of the same order of magnitude. Differences are probably due to the winds at the vertices of the triangles not being completely representative of the wind field along the sides of the triangles or of the layers between the reporting levels, or to wind direction being reported only to 10 degrees.

In general the changes in the divergence patterns about the time of heavy rainfall were more prominent at the

TABLE 2.—*Vertical motions (cm. sec.$^{-1}$), January 21–22, 1957*

	Miami, Tampa, Cocoa triangle		Miami, Cocoa, Grand Bahama triangle	
	1500 GMT Jan. 21	0300 GMT Jan. 22	1500 GMT Jan. 21	0300 GMT Jan. 22
w of tropopause* (cm. sec.$^{-1}$)	+2	+1	+1	+1
Maximum vertical velocity in troposphere computed with $w_0=0$	+2	+13	+18	+4
Maximum vertical velocity in troposphere computed by assuming w at 40,000 feet = w of tropopause	+26	+5	+37	+10

*Mean rate of change of height of tropopause for 24-hour period centered on time of observation.

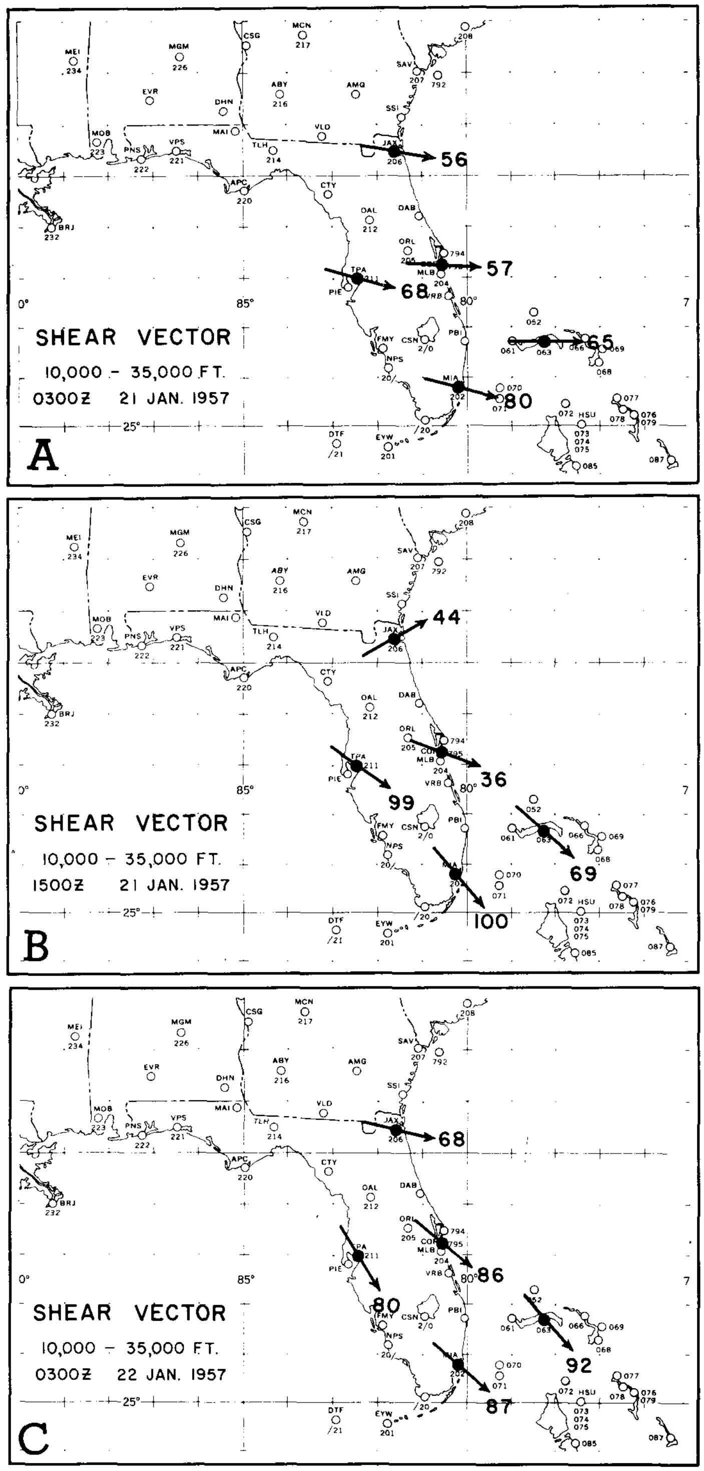


FIGURE 7.—Vertical wind shears (kt.) 10,000–35,000 feet. (A) 0300 GMT, Jan. 21; (B) 1500 GMT, Jan. 21; (C) 0300 GMT, Jan. 22, 1957.

upper than at the lower levels. The time changes in the maximum vertical velocities computed on the assumption that w at 40,000 feet equals w of tropopause were more closely correlated with changes in intensity of the rainfall in the respective triangles than were the maximum velocities computed with $w_0=0$. Thus, for this case, changes in the divergence patterns in the upper troposphere gave strongest clues concerning rainfall prediction.

4. VERTICAL WIND SHEAR

The vertical wind shear was very strong on the day of the rainfall. In figure 7 we have the charts from 0300 GMT on the 21st through 0300 GMT on the 22d. The 10,000–35,000-ft. wind shears range in value from 36 to 100 kt. in this period. These shears, just as did the divergence computations, strongly suggest that extreme vertical motion was taking place [7, 8]. The strong shears indicate intense thermal gradients and the observed winds should have caused greater advective warming in the upper troposphere than was recorded at fixed levels. Therefore, the shears give indications of ascending motion.

5. CONCENTRATION OF RAINFALL

It is believed that juxtaposition of land and water masses helped keep the heavy rainfall in the relatively small area between West Palm Beach and Lake Okeechobee for several hours. Particularly in the low levels the winds would be subject to less frictional drag while blowing over the ocean surface than over land. Thus the air blowing from the ocean to land naturally would have established convergence patterns near the coast. As the air again blew over water, i.e., Lake Okeechobee, there would have been an acceleration of the wind speed and increased divergence due to less frictional drag. The radar pictures [1] (also see fig. 2) indicate that for several hours small showers developed near and just east of the Atlantic Coast, moved westward into the hard core rain area, and dissipated as they moved farther westward. This suggests that the low-level wind field was triggering the showers and that the high-level wind field with its intense divergence pattern was accelerating the vertical motion and causing the rain to be so heavy.

6. CONCLUSIONS

Synoptic evidence supports the hypothesis that the heavy rain was caused by the superposition of a high-level area of divergence over a low-level area of convergence. The location of the rain was influenced by the location of the land and water masses.

If we are to attempt to forecast such heavy localized rainfall and, in particular, to identify the area in which the heavy rainfall will occur, we will need better techniques for forecasting the formation and movement of high-level jet streams and particularly the microstructure features of the speed field in the jet stream.

ACKNOWLEDGMENTS

The authors are indebted to the University of Miami Radar Meteorological Laboratory (Mr. Homer W. Hiser, Director) for permission to study the time-lapse pictures of the radarscope (assembled and edited by Mr. L. F. Conover). They also had valuable discussions of the work with several members of the staff of the National Hurricane Research Project, and Drs. H. Riehl, N. E. LaSeur, and Charles L. Jordan.

REFERENCES

1. H. W. Hiser, L. F. Conover, and H. V. Senn, "Investigation of Rainfall Measurement by Radar," *Final Report* to U.S. Weather Bureau, Contract Cwb-9012, Marine Laboratory and Radar Research Laboratory, Univ. of Miami (No. 57–12), 66 pp., 1957.
2. H. Riehl, M. A. Alaka, C. L. Jordan, and R. J. Renard, "The Jet Stream," *Meteorological Monographs*, vol. 2, No. 7, American Meteorological Society, Boston, 1954, 100 pp.
3. H. Riehl, K. S. Norquest, and A. L. Sugg, "A Quantitative Method for the Prediction of Rainfall Patterns," *Journal of Meteorology*, vol. 9, No. 5, Oct. 1952, pp. 291–298.
4. M. A. Alaka, "A Case Study of an Easterly Jet Stream in the Tropics," *Tellus*, vol. 10, No. 1, Feb. 1958, pp. 24–42.
5. Roderick Graham, "A New Method of Computing Vorticity and Divergence," *Bulletin of the American Meteorological Society*, vol. 34, No. 2, Feb. 1953, pp. 68–74.
6. John C. Bellamy, "Objective Calculations of Divergence, Vertical Velocity, and Vorticity," *Bulletin of the American Meteorological Society*, vol. 30, No. 2, Feb. 1949, pp. 45–49.
7. H. A. Panofsky, "Methods of Computing Vertical Motion in the Atmosphere," *Journal of Meteorology*, vol. 3, No. 2, June 1946, pp. 45–49.
8. B. I. Miller, "High Level Vertical Motion in Relation to Tropical Rainfall," *Monthly Weather Review*, vol. 81, No. 10, Oct. 1953, pp. 319–325.